

# VERTICAL TEMPERATURE GRADIENTS IN A BEECH FOREST IN CENTRAL OHIO<sup>1</sup>

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Vertical temperature gradients in forests are the result of, and at the same time reflect, a complex of microclimatic layers, formed and controlled in large part, by the vegetation itself. Density of the canopy and luxuriance of the understory as well as the presence or absence of other layer societies are the primary controls of these gradients in the summer season. Geiger (1927) concludes "that the crown surface [canopy] is the main cause of changes in the condition of the air in a forest; the soil surface functions as a surface in the meteorologic sense only under experimental conditions." More precisely, the canopy is the primary control of air conditions in a forest during the verdant season; the substrate functions as a major control only during the leafless season, rarely during the season of closed canopy.

Not only are diurnal temperature regimes at various levels in forests different from each other from season to season, but there are also considerable differences in temperature between various levels during daily regimes of a single season. The literature concerning these phenomena is fragmentary and deals mostly with short-time measurements, some of them for less than a day's duration. Some studies have been made in various levels of forest vegetation, but most notably in the canopy and near the substrate. No all-season, continuous, simultaneous measurements of temperature at different levels in a forest, from beneath the substrate to the canopy layer, are known to the writer.

Fowells (1948) described a temperature profile in a pine forest in California. He found that the highest average maximum ( $83.6^{\circ}$ )<sup>2</sup> and lowest average minimum ( $31.8^{\circ}$ ) air temperatures for the month of August occurred at the forest floor. Lowest average maximum ( $80.4^{\circ}$ ) and highest average minimum ( $34.4^{\circ}$ ) air temperatures for the same period were recorded at a station 120 feet above the forest floor. This is in direct contrast to summer temperature phenomena for a Beech Forest reported in the present paper. Geiger (1950) stated that air temperatures at 2.4 m are considerably higher during the day and lower at night in an open fir stand than in a fir stand with pine undergrowth. The more dense the canopy, the more slowly the air beneath it mixes with the outside air. Wolfe, Wareham, and Scofield (1949) have made weekly min-max temperature studies near the substrate in several types of forest vegetation over a period of five years. Geiger (1950) briefly discussed a few investigations of forest temperatures and reported that Ungeheuer (1934) found that higher temperatures occur in the canopy during the diurnal course of the temperature march than in the trunk space and 3 m above the ground in a 136-year-old beech stand. Geiger and Amann (1931, 1932) found temperatures in an oak forest lowest and most uniform 3 m above the forest floor, highest and most unsettled in the canopy, and decreasing with decreasing heights within the forest during diurnal temperature regimes. Von Lorenz-Libernau (1890) stated that, at night, forest temperature differences are slight between the various levels. Either the whole air mass is isothermal or, if the canopy is sufficiently dense, the cold air remains above it. Geiger (1950) said, with reference to a pine stand, that minimum temperature differences occur between the space above the crown and above the forest floor about noon when the sun penetrates into the forest and conduction is most highly developed.

<sup>1</sup>Department publication 532. Personal acknowledgments are made to John N. Wolfe.

<sup>2</sup>All temperatures are Fahrenheit.

## THE PROBLEM AREA

The present study of vertical temperature gradients was conducted in a Central Ohio Beech Forest. Measurements were made in an area near the center of an 11-acre forest tract. On an acre quadrat, in the center of the tract, are 82 trees over 5 inches in diameter. The number of trees in the various size classes are indicated in table 1. DeSelm (1952) has described the soils, topography, and vegetation in greater detail.

TABLE 1

*Tree species in the problem area and numbers of individuals over 5 inches in diameter*

Diameter (inches)	Species						Totals
	Beech	Sugar Maple	Elm	White Ash	Black Cherry	Red Oak	
5-10	3	2	6	4	3	0	18
11-15	9	4	3	2	0	0	18
16-20	22	4	2	1	0	0	29
21-25	8	1	2	0	0	0	11
26-30	5	0	0	0	0	0	5
31-38	0	0	0	0	0	1	1
Totals	47	11	13	7	3	1	82

## METHODS OF TEMPERATURE MEASUREMENT

Temperatures were first recorded April 30, 1950, and measurements were continued through December 31, 1950. During this study, temperatures were obtained at eight stations at different levels in the forest complex, from four feet below the forest floor to 80 feet above it.

A Leeds and Northrup Micromax Recorder (Model S 40000 series) was used for recording all temperatures. The thermocouples were of 16-gauge iron-constantan wire and those above ground were so placed that they were exposed in a vertical straight line 18 inches from the tree on which the lead wires were attached. The lead wires from each station were connected to the Micromax which recorded the temperature of that station once every eight minutes. Thus, a continuous record for the whole period of the investigation was recorded. Thermocouples were located and continuous records obtained from points four feet below leaf litter, six inches below leaf litter, just under leaf litter, just over leaf litter, five feet above leaf litter, 20 feet above leaf litter and 20 feet below the lowest branches of the canopy trees, 62 feet above leaf litter, and 82 feet above leaf litter near the top of the canopy.

## FOREST TEMPERATURE REGIMES IN SUMMER

In summer,<sup>3</sup> the over-all range of temperature in the forest is from 46° to 89°. Both minimums and maximums were a few degrees below the extremes (50°-95°) of the macroclimate.<sup>4</sup> This is in agreement with many observations that forested

<sup>3</sup>Seasons have been delimited on the basis of phenological phenomena according to the criteria used by Wolfe, Wareham, and Scofield (1949). The calendar dates used in this paper are: summer, May 23-September 11; fall, September 12-November 3; winter, November 4-December 31 (incomplete); spring, April 30-May 22. No data were obtained in early spring.

<sup>4</sup>The macroclimate is here considered to be represented by Weather Bureau data (Columbus, Ohio, station).

areas are cooler than non-forested areas. In table 2, the summer minimums and maximums in the forest are compared with the macroclimatic extremes.

TABLE 2

*Maximum and minimum temperatures for summer (1950) at eight different levels in a Beech Forst compared with those of macroclimate.*

	Station								Weather Bureau
	-4 ft.	-6 in.	Under leaf litter	Leaf litter surf.	5 ft.	20 ft.	62 ft.	82 ft.	
Max. Temp.	61°	66°	72°	83°	84°	86°	86°	89°	94°
Date	7/17 9/6	7/20 8/18	7/17 8/17	7/17	8/17	8/17	8/17	8/17	6/26 8/17
Min. Temp.	51°	54°	54°	49°	48°	48°	48°	46°	50°
Date	5/23	5/23	5/23	6/18	6/18	6/18	6/18	6/18	6/4
Range	10°	12°	18°	34°	36°	38°	38°	43°	44°

Maximum temperatures become progressively higher with ascent from the lowest station four feet below the leaf litter, and minimums become progressively lower from six inches below the litter upwards. Thus the ranges become progressively greater, and in the canopy in summer, approximate the range in temperature of the macroclimate.

Even these extremes show the striking similarity in temperature regimes at various levels of the forest beneath the canopy and above the substrate in summer. Average diurnal differences in the summer profiles are small, as it is indicated in figure 1. Moreover, the actual seasonal temperature conditions, indicated in table 3, show a remarkable similarity and narrow amplitude. For example, temperatures over the substrate are between 60° and 79° 82 percent of the summer season; in the same range at five feet, 81 percent of the time; at 20 feet, 79 percent; and at 62 feet, 78 percent. The striking differences in temperature climates in the forest in summer are between those levels below the substrate and those above it.

TABLE 3

*Temperatures at eight stations in a Beech Forest during summer compared in terms of percentage of total time at various degree ranges.*

	Station							
	-4 ft.	-6 in.	Under leaf litter	Leaf litter surf.	5 ft.	20 ft.	62 ft.	82 ft.
80°-89°	0	0	0	2	4	5	5	6
70°-79°	0	0	6	32	34	34	31	33
60°-69°	30	88	79	50	47	45	47	47
50°-59°	70	12	15	15	14	15	15	13
40°-49°	0	0	0	1	1	1	2	1

Soil temperatures in summer at a depth of four feet range from 51° to 61°, rising gradually from the lower temperature to the higher at the rate of one degree per week until mid-July. During late July and August there is slight fluctuation from 61° during early morning to 60° during the day.

At a depth of six inches, the summer temperature range is 12 degrees, from 54° to 66°. The maximum is attained in mid-July, the rise from 54° occurring at the rate of about a degree per week. Daily fluctuations, however, are greater than at four feet, but rarely are as much as three degrees. Temperatures are between 61° and 66° 88 percent of the summer season (table 3).

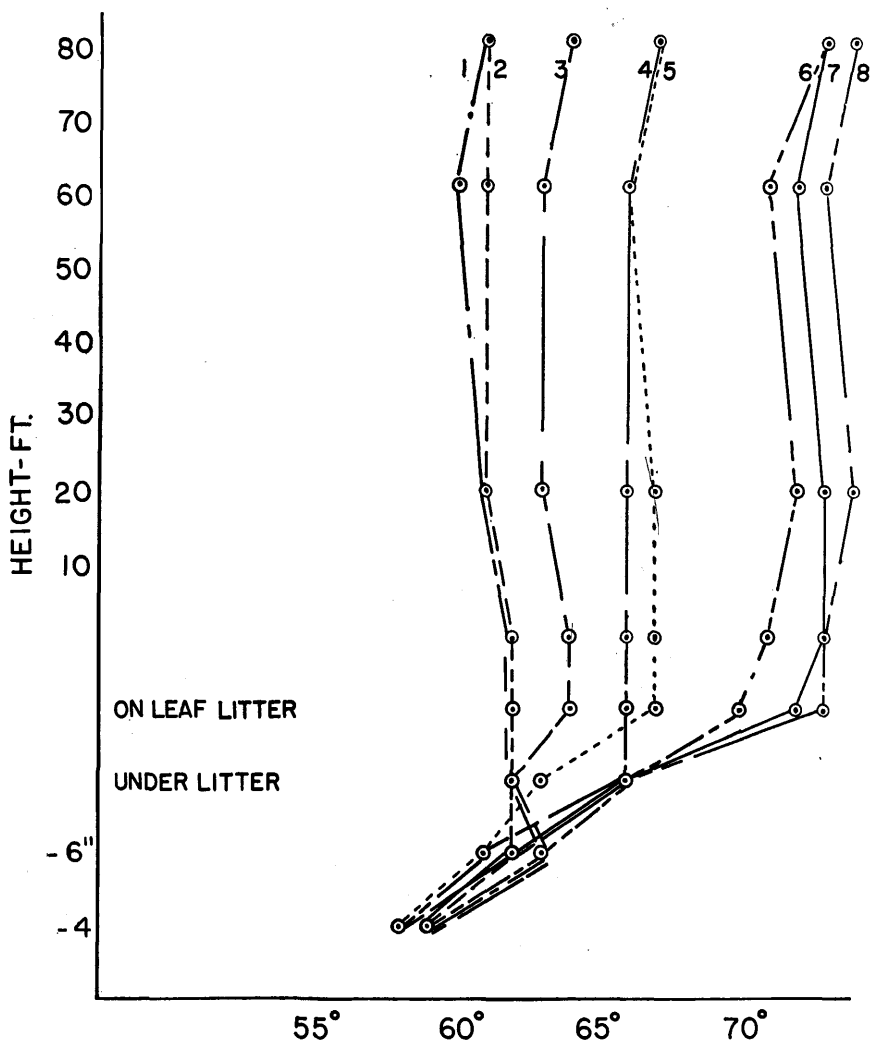


FIGURE 1. Average vertical temperature gradients in a beech forest in summer at different hours of the day. In this and following figures, curve number 1 represents the gradient at 3 A.M., 2 at 6 A.M., 3 at 12 midnight, 4 at 9 P.M., 5 at 9 A.M., 6 at 6 P.M., 7 at 3 P.M., and 8 at 12 noon.

The summer temperature range under leaf litter is 18 degrees, from 54° to 72°, but temperatures are between 60° and 69° 79 percent of the time (table 3). Daily temperatures fluctuate as much as nine degrees, rising one degree for approximately every three degree rise in temperature above the leaf litter, and decreasing at about the same rate.

FOREST TEMPERATURE REGIMES IN FALL

In fall, the over-all range of temperature in the forest was between 34° and 85°. The minimum was a few degrees below and the maximum a few degrees above the extremes (38°-83°) of the macroclimate. With thinning of the canopy as the leaves begin to fall, fluctuations in temperature at various levels become greater than in summer. In table 4, the fall minimums and maximums are compared with the macroclimate extremes.

TABLE 4  
*Maximum and minimum temperatures for fall (1950) at eight different levels in a Beech Forest compared with those of macroclimate.*

	Station								Weather Bureau
	-4 ft.	-6 in.	Under leaf litter	Leaf litter surf.	5 ft.	20 ft.	62 ft.	82 ft.	
Max. Temp.	60°	63°	67°	82°	77°	81°	84°	85°	83°
Date	9/17 9/24	9/22	9/19	10/21	10/18	10/21	10/18	10/17	10/31
Min. Temp.	56°	54°	46°	36°	36°	35°	35°	34°	38°
Date	10/23 10/26	10/26	9/25	10/26	10/26	9/24	9/24	9/24	9/24
Range	4°	9°	21°	46°	41°	46°	49°	51°	45°

Maximum temperatures are progressively higher from four feet below the leaf litter to the leaf litter surface. A decrease from the temperature at the leaf litter surface occurs at five feet, after which temperatures become higher with ascent. Thus, during fall, two maximums occur: one in the canopy and a second weak maximum over the leaf litter (see also fig. 2). Minimum temperatures become progressively lower from four feet beneath the leaf litter upward to the canopy. The range at the surface of the leaf litter closely approximates the range in temperature of the macroclimate and the range at the canopy is greater than the range of the macroclimate during fall.

TABLE 5  
*Temperatures at eight stations in a Beech Forest during fall compared in terms of percentage of total time at various degree ranges.*

	Station							
	-4 ft.	-6 in.	Under leaf litter	Leaf litter surf.	5 ft.	20 ft.	62 ft.	82 ft.
80°-89°	0	0	0	1	0	0	1	2
70°-79°	0	0	0	8	9	12	9	13
60°-69°	12	37	41	40	38	35	36	35
50°-59°	88	63	53	35	37	36	36	35
40°-49°	0	0	6	14	14	14	14	13
30°-39°	0	0		2	2	3	4	2

The pattern of minimum extremes is strikingly similar to the average nocturnal profile (fig. 2) but the diurnal average departs considerably from the pattern of maximum extremes (table 4 and fig. 2). Diurnal differences between above-ground stations in the forest are not great except near the leaf litter, as is indicated in figure 2. However, the actual seasonal temperature conditions, indicated in table 5, are similar. Temperatures over leaf litter and at five feet above it are

between  $50^{\circ}$  and  $69^{\circ}$  75 percent of the fall season; in the same range at 20 feet, 71 percent of the time; at 62 feet, 72 percent of the time; and at 82 feet, 70 percent of the time. The most striking feature of fall temperatures is the wide range at the substrate in comparison to those of summer.

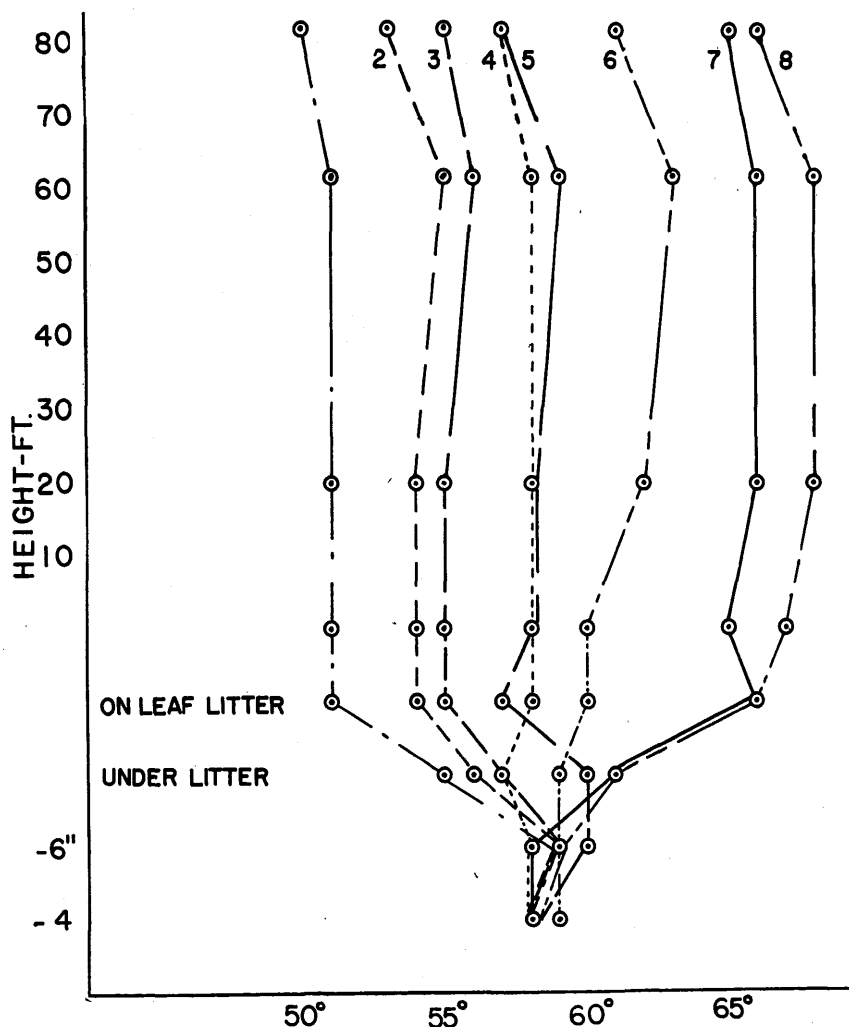


FIGURE 2. Average vertical temperature gradients in a beech forest in fall at different hours of the day.

#### FOREST TEMPERATURE REGIMES IN WINTER

In winter, the over-all range of temperature in the forest was from  $-6^{\circ}$  to  $57^{\circ}$ . Both minimum and maximum temperatures were slightly lower than the extremes ( $-3^{\circ}$  to  $65^{\circ}$ ) of the macroclimate. In table 6 winter minimums and maximums are compared with macroclimatic extremes.

Maximum temperatures decrease progressively from a depth of four feet up to the leaf litter surface, increasing from the leaf litter surface to 20 feet, then decreasing at 62 feet and 82 feet. Maximum temperature at four feet beneath the surface is exceeded only by the maximum temperature at 20 feet. Minimum temperatures decrease from four feet beneath the surface to the canopy, but higher minimum air temperatures occur at 20 feet and 62 feet than at five feet and 82 feet. Thus the greatest range occurs at five feet but is lower than the temperature range of the macroclimate.

TABLE 6

*Maximum and minimum temperatures for winter (1950) at eight different levels in a Beech Forest compared with those of macroclimate.*

	Station								Weather Bureau
	-4 ft.	-6 in.	Under leaf litter	Leaf litter surf.	5 ft.	20 ft.	62 ft.	82 ft.	
Max. Temp.	56°	55°	50°	47°	54°	57°	56°	56°	65°
Date	11/4	11/4	11/4	12/6	12/3	12/2	12/2	12/2	11/7
Min. Temp.	40°	37°	32°	17°	-6°	3°	1°	0°	-3°
Date	12/28 12/31	12/28 12/31	12/28	12/27	12/27	12/27	12/27	12/27	12/27
Range	16°	18°	18°	30°	60°	54°	55°	46°	68°

The patterns of minimum and maximum temperature extremes are strikingly similar to the average daily profiles indicated in figure 3. Daily differences in average temperature during winter do not exceed six degrees. However, because the thermocouple at the leaf litter surface was snow-covered much of the season, the actual seasonal temperature conditions at ground level differ conspicuously from the various other levels (table 7). For example, temperatures beneath the snow<sup>5</sup> range from 20° to 39° 88 percent of the winter season; in the same range at

TABLE 7

*Temperatures at eight stations in a Beech Forest during winter compared in terms of percentage of total time at various degree ranges.*

	Station							
	-4 ft.	-6 in.	Under leaf litter	Leaf litter surf.	5 ft.	20 ft.	62 ft.	82 ft.
50°-59°	16	9	2	0	2	3	3	3
40°-49°	84	74	46	8	10	9	7	8
30°-39°	0	17	52	59	34	34	24	23
20°-29°	0	0	0	29	34	38	44	41
10°-19°	0	0	0	4	15	13	18	20
0°-9°	0	0	0	0	4	3	4	5
-10°- -1°	0	0	0	0	1	0	0	0

five feet and 62 feet, 68 percent of the time; at 20 feet, 72 percent of the time; and at 82 feet, 64 percent of the time.

Soil temperatures in winter, at a depth of four feet, range from 56° to 40°, decreasing at the rate of two degrees per week. Lowest temperatures occur

<sup>5</sup>No thermocouple was installed at the snow surface.

around noon and highest temperatures around midnight. Eighty-four percent of winter season temperatures occur between  $40^{\circ}$  and  $49^{\circ}$ .

Soil temperatures at a depth of six inches range from  $37^{\circ}$  to  $55^{\circ}$ , with temperatures above  $50^{\circ}$  occurring in the first week of winter only. Daily fluctuations of four degrees are common, with highest daily temperatures occurring around midnight and lowest daily temperatures around noon.

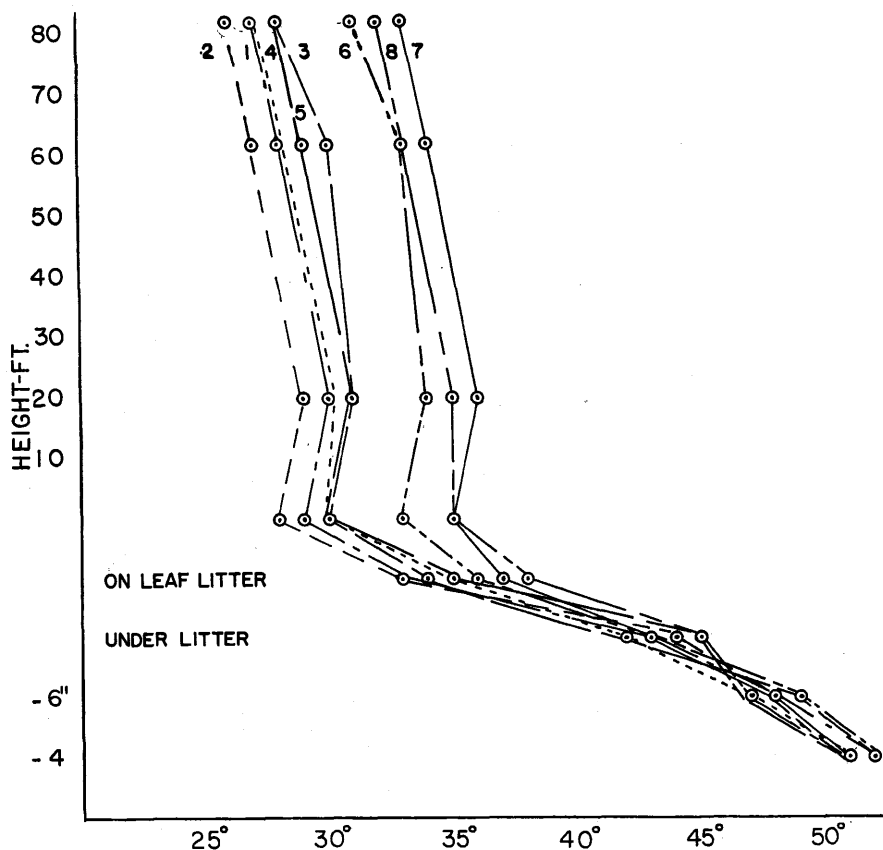


FIGURE 3. Average vertical temperature gradients in a beech forest in winter at different hours of the day.

Temperatures under leaf litter range from  $32^{\circ}$  to  $50^{\circ}$ , with temperatures between  $32^{\circ}$  and  $39^{\circ}$  occurring 52 percent of the time. Although zero and sub-zero air temperatures occur, temperatures under leaf litter are never lower than  $32^{\circ}$ . Daily temperature fluctuations exceeding five degrees are very rare at this station during the winter season.

Occurrence of highest air temperatures at 20 feet, lowest air temperatures at five feet, the narrow range of temperatures at the leaf litter surface, and the small range of substrate temperatures are outstanding features of the temperature climate in the forest during winter.



EFFECT OF SNOW COVER

During winter conditions, snow not infrequently is an additional factor in control of temperatures in the upper soil horizons. On November 23, 1950, a cold front accompanied by snow entered the problem area. By noon of November 24, the temperature under the snow was 28° while the temperature five feet above<sup>6</sup> the snow was 14°. During the days following, until air temperatures became higher than 25°, the minimum differences under snow and five feet above exceeded 10 degrees.

On December 7, a cold front without snow entered the area. The temperature at the leaf litter dropped more slowly than the temperature five feet above. When air temperatures were at a minimum, temperature at the leaf litter was three degrees higher than at five feet above. In the following days, temperatures at the leaf litter were seldom greater than, and usually the same as temperatures five feet above the leaf litter.

FOREST TEMPERATURE REGIMES IN SPRING

During the spring season, the over-all temperature range is from 35° to 121°. The over-all maximum is much higher and the minimum is lower than the extreme temperature (41°–87°) of the macroclimate. In table 8, maximum and minimum temperatures<sup>7</sup> are compared with the macroclimatic extremes.

TABLE 8

Maximum and minimum temperatures for spring (1950) at eight different levels in a Beech Forest compared with those of macroclimate.

	Station								Weather Bureau
	–4 ft.	–6 in.	Under leaf litter	Leaf litter surf.	5 ft.	20 ft.	62 ft.	82 ft.	
Max. Temp.	52°	58°	92°	121°	90°	78°	78°	78°	87°
Date	5/21	5/5	5/5	5/5	5/5	5/14	5/14	5/14	5/5
Min. Temp.	45°	47°	40°	37°	35°	45°	44°	45°	41°
Date	4/30	5/2	5/8	5/8	5/8	5/19	5/19	5/19	5/7
Range	7°	11°	52°	84°	55°	33°	34°	33°	46°

Maximum temperatures increase from four feet beneath the surface to the leaf litter and then decrease at five feet. Minimum temperatures are highest six inches below the surface and lowest five feet above. The maximum temperature of 121° at the leaf litter surface is probably high due to exposure at the thermocouple, but the maximum temperature of 92° under the leaf litter indicates that it is probably not a great departure from the real temperature.

The pattern of maximum temperature extremes is similar to the average profile at 12 noon in spring (fig. 4), while the other average profiles are in contrast to the pattern of either the maximum or minimum extremes (fig. 4 and table 8). Daily fluctuations in temperature are great during spring. Moreover, the actual seasonal temperature conditions differ conspicuously at the various levels (table 9). For example, temperatures at the leaf litter surface are above 80° over 7 percent of the time but do not reach 80° at any other level. The wide distribution of temperature

<sup>6</sup>Nearest thermocouple to the snow surface.

<sup>7</sup>Maximum and minimum temperature data at 20 feet, 62 feet, and 82 feet were not obtained for the first 15 days of the investigation, and these stations are therefore omitted from the comparisons.

at the leaf litter surface is the most outstanding feature of forest temperature in spring, and emphasizes the importance of the forest floor as a meteorological control at this important season.

TABLE 9

*Temperatures at eight stations in the Beech Forest during spring compared in terms of percentage of total time at various degree ranges.*

	Station							
	-4 ft.	-6 in.	Under leaf litter	Leaf litter surf.	5 ft.	20 ft.	62 ft.	82 ft.
110°-121°	0	0	0	+	0	0	0	0
100°-109°	0	0	0	1	0	0	0	0
90°-99°	0	0	+	2	+	0	0	0
80°-89°	0	0	+	4	3	0	0	0
70°-79°	0	0	2	10	13	11	11	15
60°-69°	0	0	17	30	30	40	38	33
50°-59°	47	90	70	41	42	42	42	44
40°-49°	53	10	10	11	11	7	9	8
30°-39°	0	0	0	+	+	0	0	0

Soil temperatures at a depth of four feet range from 45° to 52°, rising at the rate of two degrees per week through the season. Daily maximum temperatures occur from late afternoon to midnight and lowest daily temperatures occur from midnight to noon. Soil temperatures at a depth of six inches range from 47° to 58°, rising at the rate of three degrees per week as the season progresses. Highest daily temperatures occur in the evening and lowest daily temperatures occur around noon.

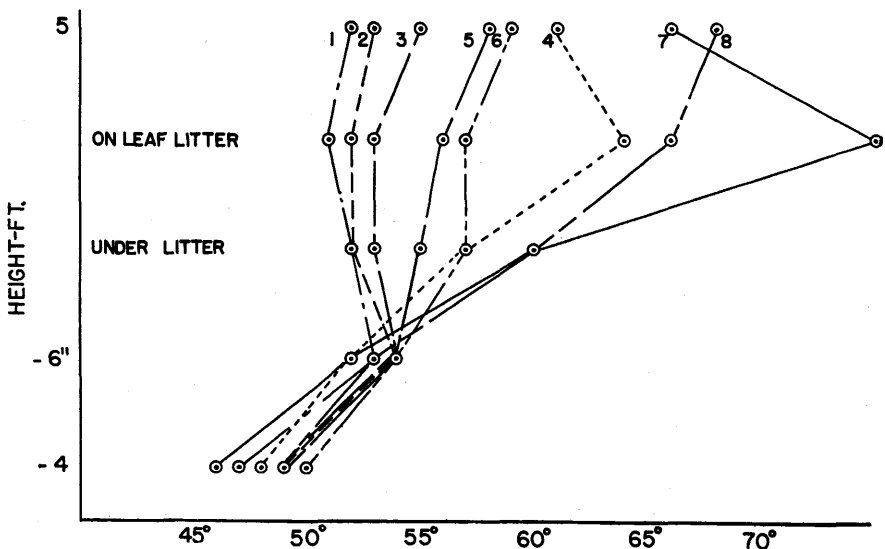


FIGURE 4. Average vertical temperature gradients in a beech forest in spring at different hours of the day.

Temperatures just under the leaf litter fluctuate more and have a wider range, 40°-92°, during spring than at any other season. Daily fluctuations may be as great as 33 degrees and fluctuations of 15 degrees are very common. Temperatures occur in a range of 50° to 69° 71 percent of the time.

## SUMMARY

Temperatures were measured at eight different levels in a Central Ohio Beech Forest continuously from April 30 through December 31, 1950, by means of thermocouples attached to a Leeds and Northrup Micromax Recorder. Thermocouples were located four feet below the leaf litter, six inches below the leaf litter, just under the leaf litter, just above the leaf litter, five feet above leaf litter, 20 feet above leaf litter and 20 feet below the lowest branch, 62 feet above leaf litter, and 82 feet above leaf litter, near the crown surface.

Data were compiled to show vertical temperature gradients and temperature regimes at various levels during different seasons of the year.

1. In summer, the greatest extremes of temperature ( $46^{\circ}$  to  $89^{\circ}$ ) occur in the canopy and temperature regimes at other levels above and below the forest floor are more stable than at any other season. At this season, the temperature regimes beneath the canopy and above the substrate are nearly uniform (no stratification) because of canopy control of the weather beneath it. Soil temperatures are higher near the surface ( $54^{\circ}$  to  $66^{\circ}$ ) than at a depth of four feet ( $51^{\circ}$  to  $61^{\circ}$ ).

2. In fall, greatest extremes of temperature ( $34^{\circ}$  to  $85^{\circ}$ ) also occur in the canopy, but there is some stratification due to thinning of the canopy by leaf fall and penetration of more sunlight to the forest floor than in summer. Minimum soil temperatures are higher in the lower soil regions than near the surface.

3. Winter minimum temperatures are lowest near the substrate ( $-6^{\circ}$ ) but temperature regimes at all levels are more uniform than in the summer as a result of greater turbulence in the absence of the canopy. In the soil, minimum and maximum temperatures are slightly lower near the surface than at a depth of four feet. Beneath the leaf litter, temperatures do not go below freezing, with or without snow cover. In the upper soil, temperatures are between  $40^{\circ}$  and  $49^{\circ}$  74 percent of the winter period, but air temperatures occur in that range from seven to ten percent of the time and are lower than that from 88 to 90 percent of the time.

4. Minimum and maximum air temperatures in spring occur at the lower levels, the leaf litter surface sometimes measuring over  $100^{\circ}$ . The forest floor is the effective meteorological surface at this season, and the widest range of temperatures of the year occur there. Stratification above this layer is not pronounced because turbulence is still great in the absence of the canopy. Soil temperatures are high near the surface (up to  $92^{\circ}$ ) and diffusion of heat downward is more rapid than at any other season.

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The Ohio Journal of Science award for excellence in research for 1952 was made to Dr. E. R. Caley at the Annual Banquet and Business Meeting of The Ohio Academy of Science at Kent State University on April 18, 1952. Dr. Caley's paper "Chemical Examination of an Ancient Sheet of Metal of Unique Composition Found in Greece," appeared in the May number of the Journal.